Pacific Signature of Global Warming: “El Niño” or “La Niña”?

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The response of the tropical Pacific to increasing greenhouse gases represents an exciting intersection of theory, modeling, and observations. In this manuscript, we contrast competing theories for the response of the tropical Pacific to global warming, illustrate the utility of models for understanding and reconciling these theories, and highlight the need for improved instrumental and paleoclimatic reconstructions to better evaluate the fidelity of current model projections.

There is a long-standing debate in the climate community on how the tropical Pacific will respond to increased greenhouse gases: will the structure of changes in the ocean surface temperature more closely resemble an El Niño or a La Niña? *[e.g., Knutson and Manabe 1995, Clement et al. 1996, Meehl and Washington 1996, Cane et al 1997, Cobb et al 2003, Collins et al 2005, Vecchi et al 2006, Zhang and Song 2006]* This distinction is of profound significance, since tropical Pacific conditions impact a range of weather phenomena including tropical cyclone activity, global patterns of drought and flood, as well as agricultural productivity and oceanic biological activity. The dispute extends beyond global warming, with El Niño and La Niña-like responses being invoked as frameworks for interpreting past climate changes on timescales of centuries to millions of years *[e.g., Koutavas et al 2002, Stott et al 2002, Mann et al 2005, Wara et al 2005]*.

There is substantial modeling and observational literature advocating the perspective that the response to greenhouse gas forcing will result either in a more El Niño-like or more La Niña-like, and these opposing points of view remain to be reconciled. The mechanisms proposed for both types of response are fundamentally different: those behind a more La Niña-like state originate primarily through the ocean, while those that suggest a more El Niño-like state are rooted in the atmosphere. The terms ‘El Niño-like’ and ‘La Niña-like’ refer to the tendency for the time-mean sea surface temperature (SST) gradient across the equatorial Pacific to either decrease or increase, without implying a change in frequency or intensity of El Niño variability.

Theoretical Basis

The basis for the La Niña-like point of view is the “Ocean Thermostat” mechanism *[Clement et al 1996, Cane et al 1997]*, in which a heating of the tropics leads to an increase in the zonal temperature gradient across the equatorial Pacific. In the east, where the thermocline is shallow, cooling by upwelling opposes the surface heating to produce a smaller temperature change than in the west Pacific - where the response is primarily thermodynamic. The increased zonal SST gradient leads to increased surface easterlies, driving further cooling by upwelling, further increasing the SST gradient.

An El Niño-like response to increased greenhouse gases may be expected since models and theory indicate that the tropical atmospheric circulation should weaken in response to a warming climate *[Betts and Ridgway 1989, Knutson and Manabe 1995, Held and Soden 2006]*. This weakening is primarily manifest as a reduction in the intensity of the zonal overturning of air across the Pacific (*i.e.,* the Walker circulation) *[Held and Soden 2006]* and a decline of the equatorial easterlies that, along with other atmospheric feedbacks *[Knutson and Manabe 1995, Meehl and Washington 1996]*, results in a reduction in equatorial Pacific SST gradient.

Numerical Model Experiments

The mechanisms governing the tropical Pacific's response to global warming emerge from a hierarchy of climate models with simplifications made to either the ocean or the atmosphere. For example, in the Cane-Zebiak model used by *Clement et al [1996]*, the representation of atmospheric processes is simplified such that the atmospheric circulation does not weaken in response to a warming. In this configuration, the 'Ocean Thermostat' mechanism dominates and a La Niña like state is predicted in response to warming (Fig. 1.a).

On the other hand, the weakened Walker Cell dominates the tropical Pacific response to increased CO_2 in global climate models (GCMs) that have ocean models with simplified (mixed-layer) representations. In this configuration, the effect of ocean dynamics is fixed, eliminating the ‘Ocean Thermostat’, but not the ‘Weaker Walker’ mechanism, thus leading to a reduction of the zonal SST gradient and an El Niño-like state. This can be seen in the response to CO_2 doubling from thirteen models from the Third Coupled Model Intercomparisson Project (CMIP3) database (Fig.1.b).

But what happens when both mechanisms are possible? For this we now turn to the same set of GCMs models as in Fig. 1.b, but now with a full representation of both oceanic and atmospheric processes. These GCMs still show relatively zonally-uniform warming, with a slightly larger warming in the central Pacific than the west (Fig. 1.c). Clearly, the ’El Niño-ness‘ of the signal is diminished relative to the case without ocean dynamics (Fig. 1.b). We suggest that this overall pattern is a superposition of both the ‘Ocean Thermostat’ and the ‘Weaker Walker’ mechanisms. Further analysis is necessary to quantify the relative influence of these (and possibly other) mechanisms.

Current model projections do not show a systematic response of their El Niño variability to global warming *[e.g., Merryfield 2006]*. Though changes in mean state of the Pacific provide a foundation to understand the response of El Niño variability to global warming, the intensity, frequency and character of El Niño involves a variety of physical processes, whose response to increased greenhouse gases is not well constrained by current models.

Instrumental Measurements

A resolution of the mechanisms active within GCMs is not sufficient to settle the dispute over the response of the tropical Pacific to greenhouse forcing: for this we must turn to observations. We compare centennial trends in SST from two different reconstructions of SST in Figs. 1.d-.e. One reconstruction – HadISST *[Rayner et al. 2003]* – shows a 'La Niña-like' pattern, with an increase in the zonal SST gradient, through robust warming in the west and weak changes (including modest cooling) in the east, in qualitative agreement with *Cane et al. [1997]*. However, the NOAA extended reconstruction of SST (ERSST) *[Smith and Reynolds 2004]* shown in the lowest panel exhibits an 'El Niño-like' pattern, with more warming in the east than the west, and is consistent with recent analyses of sea level pressure data indicating a weakening of the Walker circulation *[Vecchi et al. 2006, Zhang and Song 2006]*. This discrepancy leaves one unable to confirm the fidelity of the models' partitioning of the different processes that would lead to "El Niño-like" and "La Niña-like" responses.

The time-series of the west-east difference of SST across the Pacific (δ_xSST) provides hints as to the source of the discrepancies (Fig. 2). Over most of the period 1880-present, the evolution of the two reconstructions of δ_xSST is quite similar, with the timing and amplitude of local maxima and minima corresponding across the products. However, their long-term behavior is different, between the products over two periods around the 1930s and 1980s. These periods are roughly coincident with, respectively, the period of greatest change in "bucket-to-intake" corrections of SST measurements (a correction that differs between the products) and the beginning of satellite infrared SST retrievals (satellite data is used in HadISST, but not in ERSST). Effort should be placed towards identifying the specific sources of this discrepancy and the appropriate corrections.

Proxy Data

Another way forward may be through reconstructions of local temperature and salinity using coral skeletons from the tropical Pacific over the historical record. Currently, there are only a handful of published data sets that can address this issue. Some coral records suggest a trend towards warmer and wetter conditions in the central Pacific at the end of the 20th century *[e.g., Cobb et al 2003, Urban et al 2000]*. Taken at face value, this would suggest an eastward shift of warm pool convection and more El Niño-like conditions. On the other hand, coral records from the region of the South Pacific convergence zone suggest an eastward expansion of rainfall since the mid-1880s, as occurs during La Niña events *[Linsley et al 2006]*. A more complete picture of the evolution of tropical Pacific climate of the 20th Century will emerge from additional records from various locations, incorporated into a multi-proxy, synthesized approach. For example, *Evans et al. [2002]* have constructed a framework for analyzing numerous coral records to extract the spatially and temporally coherent signals. Because the discrepancies in the reconstructions of δ_xSST arise primarily in two discrete periods (see Supplementary Figure), proxy observations spanning these periods could prove particularly useful.

Theory, models and observations present diverging views of the Pacific response to global warming. It may be possible to reconcile the different theoretical frameworks for understanding the Pacific response to increased CO_2 within state-of-the-art coupled

GCMs. However, the test of how these mechanisms operate in reality is in the hands of the observationalists, and the consequences for our understanding of the climate not only in the tropical Pacific, but in all the regions affected by ENSO, are great.

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Figure Captions:

Figure 1: Response of coupled models of varying complexity to a warming climate and observational estimates of the long-term trend in Pacific SST, normalized by tropical-mean SST change: (a) response of the Cane-Zebiak model to an imposed surface warming of 2K, normalized by 2K (adapted from *Clement et al. [1996]*); ensemble-average response of SST to CO_2 doubling from thirteen GCMs from the CMIP3 model database in (b) mixed-layer ocean GCM and (c) fully-coupled GCM configurations; 1880-2005 trends from the reconstructions of observed SST from (d) HadISST and (e) ERSST.

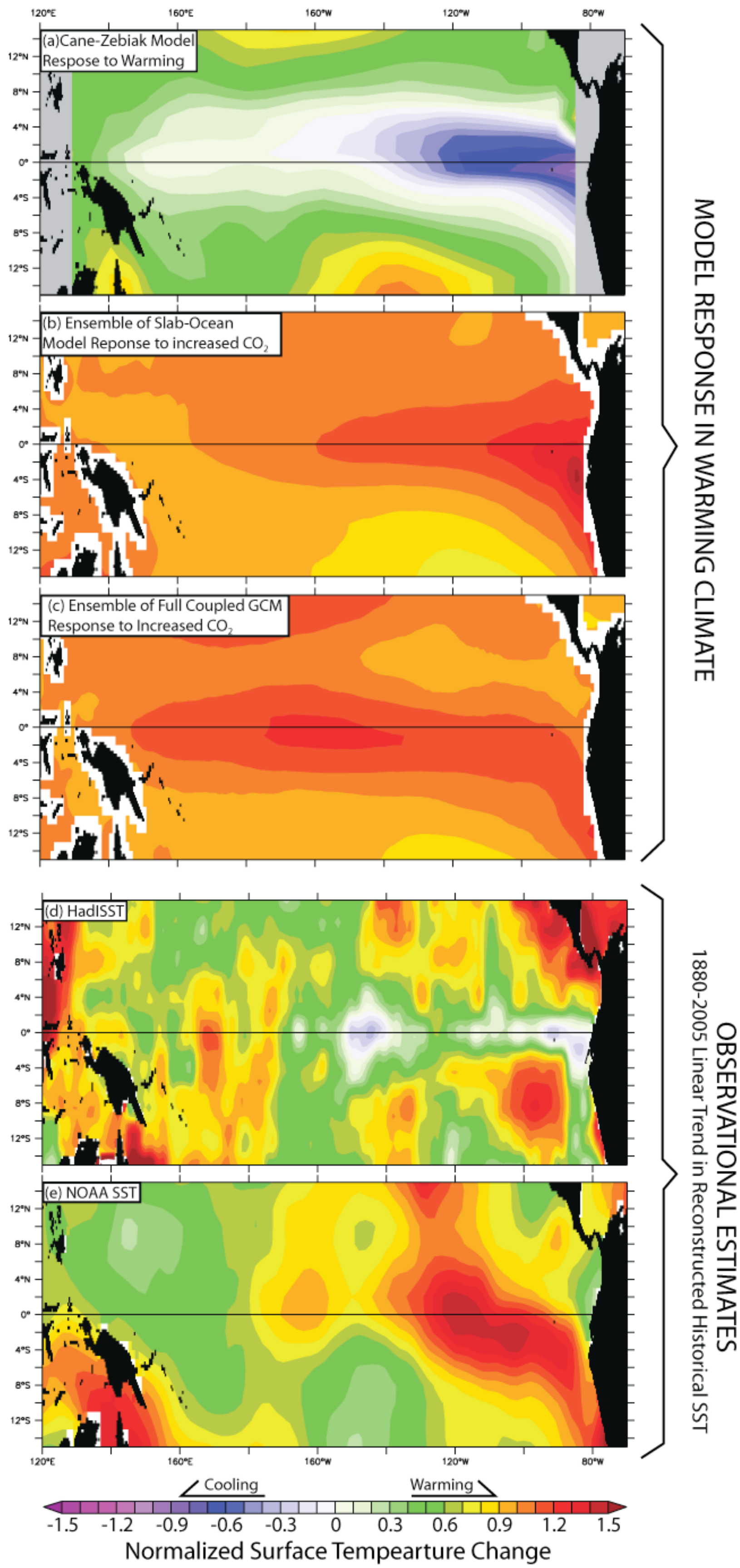
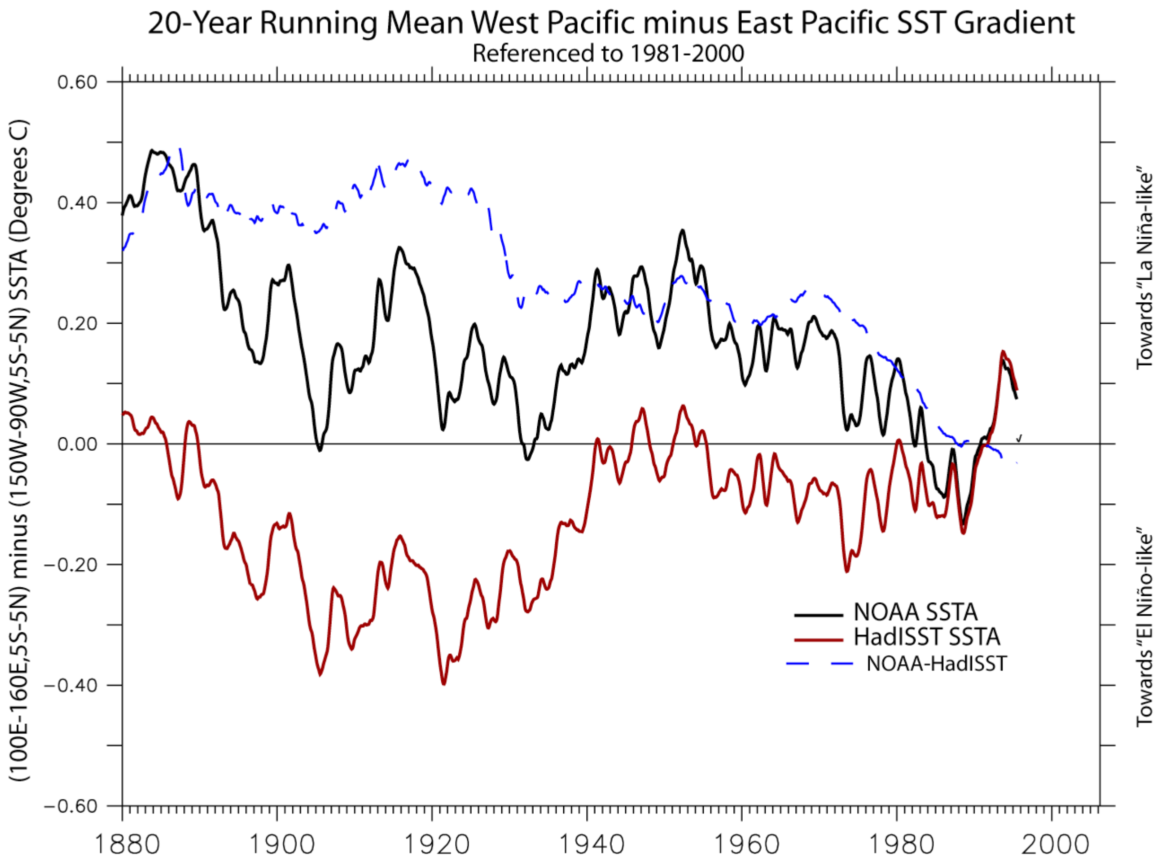

(a)Cane-Zebiak Model Respose to Warming
(b) Ensemble of Slab-Ocean Model Reponse to increased CO_2
(c) Ensemble of Full Coupled GCM Response to Increased CO_2
(d) HadISST
(e) NOAA SST
MODEL RESPONSE IN WARMING CLIMATE
OBSERVATIONAL ESTIMATES
1880-2005 Linear Trend in Reconstructed Historical SST
120°E
160°E
160°W
120°W
80°W
12°N
8°N
4°N
0°
4°S
8°S
12°S
Cooling
Warming
-1.5
-1.2
-0.9
-0.6
-0.3
0
0.3
0.6
0.9
1.2
1.5
Normalized Surface Tempearture Change

Figure 1



Supplementary Figure: Time-series of 20-year mean west minus east Pacific SST for three reconstructions of observed SST (solid lines) and for the difference of the ERSST reconstruction to the other two reconstructions (dashed lines). Units are Kelvin, and positive values indicate a more "La Niña-like" state. Data have been referenced to 1981-2000.